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Climate change impacts on boreal forest timber supply

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ABSTRACT

Recent studies have assessed the ecological effects of climate change on boreal forests; however, our understanding of the economic impacts of climate change on timber supply remains limited. Forestry is an important boreal industry; hence, it is necessary to better understand the ecological impacts that directly and indirectly affect this sector. We reviewed published literature concerning ecological impacts of climate change on biome shifts, regional forest disturbances, and tree growth, mortality and species compositional shifts in established forest stands. Subsequently, we examined how each factor influences timber supply and forestry. Tree species ranges have been and will continue migrating north to find more suitable growing conditions, but at a slower rate than climate change. Biome shifts from forests to shrub or grasslands may occur under persistent drought conditions. Warmer temperatures and lower climate moisture availability increase forest disturbances; notably fire and insect outbreaks, creating younger forests dominated by pioneer species and limiting harvestable material. While tree growth and mortality rates are spatially variable across established forest regions, tree mortality has temporally increased with climate change; accompanied by reduced growth or increased growth at a rate lower than mortality loss, resulting in a reduced rate of volume accumulation and timber available for harvest. Moreover, climate change favors pioneer species (*Pinus* spp. and *Populus* spp.) over late successional species (*Picea* spp. and *Abies* spp.). Our findings suggest that climate change has strong negative effects on boreal timber supply but may prompt operational adaptations, opening opportunities for forest industry to incorporate species such as *Populus*.

1. Introduction

The boreal forest is one of Earth's largest forest biomes, with an area of 1.2 billion hectares; stretching from Russia, across Scandinavia and throughout North America (van Lierop et al., 2015). The boreal forest constitutes approximately 30% of the world's most densely forested area (Crowther et al., 2015), while storing nearly half of the global forest carbon, primarily within soils (Gauthier et al., 2015a; Soja et al., 2007). This forest region is immensely critical to the global timber products market. Roughly 33% of lumber and 25% of paper exports in the global market originate from the boreal forest (Gauthier et al., 2015a). However, most ecological functions and processes, such as tree growth, proceed slowly in the boreal forest due to short growing seasons with severe, cold winters (Fettig et al., 2013; Kellomaki, 2000). Despite similar presences of tree genus (*Picea, Pinus, Populus, Larix,* and *Betula*), disturbance regimes and management histories and strategies differ between Eurasian and North American boreal forest regions (Gauthier et al., 2015a; Rogers et al., 2015; Schaphoff et al., 2016).

Climate change has a profound impact on global forestry, and continues to accelerate with increasing anthropogenic greenhouse gas emissions (IPCC, 2014). Higher latitudinal areas are expected to undergo the largest increases in temperature (Diffenbaugh and Field, 2013) and experience variable shifts in precipitation regimes (Gauthier et al., 2015a; Reyer et al., 2015). Changes in site conditions and frequency of disturbance regimes have also affected the boreal forest as a result of climate change (Price et al., 2013). Understanding climate change impacts on boreal forest dynamics and timber supply is crucial to the continued viability of boreal forest industry.

Timber supply, defined in this review as the quality and quantity of standing timber available for harvesting, directly impacts the forest industry; in both the short run and long run. The difference between the two timelines is the amount of time required to transition between capital investments in equipment and product development (Zhang and Pearse, 2011). Short run supply occurs within a timeframe that is too short for industry to adjust their capital stock and standing timber inventory; slower growth rates and higher rotation ages (particularly in the boreal forest) slow this process. This lack of flexibility means that industry can only adjust their variable inputs (fuel and labour) or utilize their facilities more intensively. In the long run, industry is able to reinvest in profitable areas and change supply to better suit the market

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(Zhang and Pearse, 2011). The duration of the long run depends on products (lumber or engineered wood products), industry (logging or pulp and paper) and geographic location (boreal forest or tropical). However, long run timber supply is difficult to anticipate because of a number of factors that affect trees: growth and mortality rates, disturbances, harvesting rotation schedules and demand of forest products (Zhang and Pearse, 2011). Climate change further complicates this process of product evaluation and timber supply (Sohngen, 2014). Analyses of the impacts of climate change on boreal timber supply should involve both short term and long-term research to properly forecast the implications of ecological change on the economy.

Recent advances have been made toward understanding climate change impacts on forest productivity, species range shifts and forest disturbances (Boisvenue and Running, 2006; Hofgaard et al., 2013; Kurz et al., 2008), though there have been few publications synthesizing these impacts. Several published reviews on the boreal forest and climate change include: global boreal forest health (Gauthier et al., 2015a), impacts to North American forests and ecosystems (Price et al., 2013), implications to forest carbon balance (Kurz et al., 2013; Schaphoff et al., 2016), forestry adaptation practices (Gauthier et al., 2014), and a recently proposed concept of using biodiversity to mitigate climate change impacts on ecosystem functioning (Hisano et al., 2018). However, the impact of climate change on industrial timber supply and its economic implications is an area that demands continued investigation. The existing forestry related reviews suggested that there would likely be increases in global timber supply (though high regional variation) from greater forest productivity (Kirilenko and Sedjo, 2007) leading to probable decreases in wood product prices and demand (Sohngen and Tian, 2016).

Modeling studies have addressed the economic impacts of climate change in specific countries or regions (Mendelsohn et al., 2000; Ochuodho et al., 2012; Solberg et al., 2003), whereas others have considered the forest industry in a global context (Lindner et al., 2002; Perez-Garcia et al., 2002; Sohngen et al., 2001; Tian et al., 2016). Older global timber models suggest higher timber productivity from tropical regions, compared to temperate regions with on-going climate change (Perez-Garcia et al., 2002; Sohngen et al., 2001), whereas, the latest global timber model predicts a similar overall increase in forest productivity in both regions (Tian et al., 2016). Generally, timber resources are expected to increase across the globe and result in lower product prices (Sohngen and Tian, 2016; Tian et al., 2016). However, empirical evidence from tropical forests revealed that climate change has led to greater biomass loss through tree mortality than growth gain, resulting in less standing biomass (Brienen et al., 2015). Further, these studies typically simulated consistent future disturbance regimes possibly leading to yield inaccuracies (McKenney et al., 2016). Nevertheless, these modeling studies do not specifically analyze the productivity of the boreal forest under climate change; rather they have focused on temperate and tropical forests. Therefore, modeling climate change impacts on boreal forest timber supply remains needed.

The purpose of this review is to synthesize the impacts of climate change on boreal forest dynamics directly relating to available timber supply (Fig. 1). Specifically, this review will: i) examine how climate change has affected boreal ecological processes at a variety of spatial scales (biome, regional, stand and individual levels), since the impacts to ecological processes differ across scales, ii) analyze how these ecological changes will impact timber supply, iii) detail management adaptations, and iv) identify gaps in current knowledge for future research.

2. Literature selection criteria

Papers were systematically selected for this review via the online search engine ISI Web of Science. The reference sections of selected papers were also reviewed for relevant literature. This was done in order to capture all applicable and available literature. Key words including climate change impacts, boreal forest timber supply, and forest sector implications were used in various combinations for the search. Because of the rapid development of the study topic, we focused on reviewing recent literature; largely post 2000. Literature was subsequently analysed, initially by title and abstract, and then through more in depth reading. Titles were selected by having some mention of climate change and timber supply associated ecological processes including biome shift, range shift, species composition, disturbance, growth, and mortality. Papers that did not explicitly address climate change were excluded. Both reviews and original articles were considered to gather evidence from a range of perspectives. Topics were divided into themes and research was synthesized to explain the various ways climate change impacts boreal timber supply (Fig. 1).

3. Biome shifts

Biome shifts represent a landscape's transition over time from one biome to another, such as forest biome to shrub land and/or grassland biome (Beck et al., 2011). Biome shifts are adaptations that take place between vegetation types and contrasting climates (Donoghue and Edwards, 2014); the process of transition is dependent on the state of an ecosystem and the speed of climate change. In high latitude systems, biome shifts have been observed over temporal scales of multiple years or decades (Beck et al., 2011). Climate is a key factor toward determining the geographic distribution of plant species (Fei et al., 2017; Fettig et al., 2013). As the climate changes, sites can become less suitable for certain plant species over time causing them to regress or die, whereupon other more suitable species take their place (Gonzalez et al., 2010). Biome shifts tend to occur along the edge of biomes (Davis and Shaw, 2001), as evidenced by the transition from forests to shrub lands under extended droughts (Anderegg et al., 2013; Donoghue and Edwards, 2014). Most of the world's forests are regarded as being extremely vulnerable to biome shifts as a result of climate change (Gonzalez et al., 2010), which stresses the importance of understanding the risks of shifting biomes.

Boreal forests have been seen steadily migrating northward in response to global warming. Researchers have observed shifts in plant and animal species ranges for decades, signifying the effect of changing climate (Chen et al., 2011; Parmesan and Yohe, 2003). Tree migration has been observed most clearly in areas with temperature extremes,

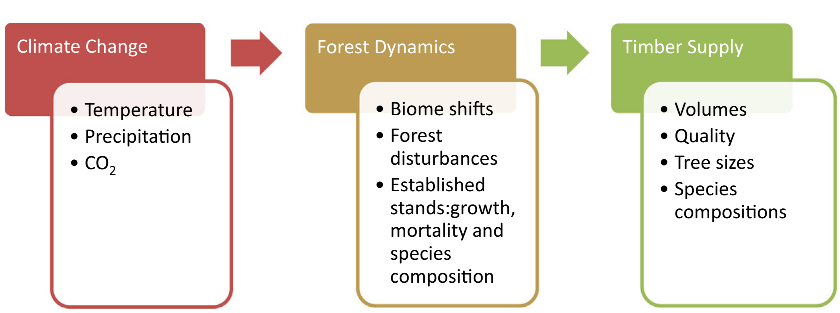

Fig. 1. A simple representation of the focus for this review and the related factors and variables associated with each. Climate change (changes in temperature, precipitation and CO_2 levels) will influence forest dynamics (growth, mortality, species range and disturbance interactions) which then impact the volume, quality, and species of timber supply available for industrial harvest and use in the boreal forest.

such as the boreal forest and tundra regions. Boreal forests have been documented as steadily growing northward into areas that were previously tundra. In Alaska, spruce populations have been declining in areas that they previously thrived in, most likely as a result of water deficiencies from high vapor pressure deficits on photosynthesis (Beck et al., 2011). Similar forest migration and compositional changes are expected in Siberia; boreal species are predicted and recorded to be migrating into more northern locations (Berner et al., 2013; Tchebakova et al., 2011). In Norway, northern regions that were once previously tree line edge are now found to be forested areas; indicating the migration of tree species (Hofgaard et al., 2013). These tree species are now moving into cooler regions so as to escape areas with high vapor pressure deficits, as well as to access more water (Fei et al., 2017). It is expected that the tundra could lose up to 50% of its area from northward expansion of the boreal (Kirilenko and Sedjo, 2007). In parallel with moving northward, southern boreal forests could retreat and shift to shrub lands or grasslands due to warming-induced climate moisture deficits (Allen and Breshears, 1998). It remains, however, unclear whether the northward expansion of boreal forests matches its southward retreat.

Under rapid climate change, species ranges continue to shift (Pecl et al., 2017), which imparts profound environmental and economic implications. It was reported that the historic migration rate of tree species (~20–40 km per century) was far slower than the rate required to avoid changing climate envelopes (~300–500 km per century) (Davis and Shaw, 2001). Recent findings estimate that tree migration rate is actually less than 100 m per year (Aitken et al., 2008) compared to the 160 km migration requirement for every degree of temperature increase (Thuiller, 2007), highlighting the disparity in migration rate requirements. More recently, there was an estimated migration rate of 16.9 km per decade, away from the equator, and 11 m per decade in elevation; still significantly lower than the required migration speed (Chen et al., 2011).This may cause unknown environmental consequences in the functioning of our ecosystems. However, assisted migration may help mitigate the mismatch between slow natural migration rates and rapid climate change (Aitken et al., 2008).

4. Regional forest disturbance patterns

Boreal forests are characterised by natural disturbances, such as fires, fungi and insect outbreaks (Gauthier et al., 2015a), where forest disturbances have severe implications to timber supply. Insects are suggested to have the greatest effect on forest harvest volumes and quality; even more so than forest fires (Logan et al., 2003; Malmstrom and Raffa, 2000), though recent findings have suggested that fires are more impactful (Hansen et al., 2013). For example, *Dendroctonus ponderosae* (mountain pine beetle) in Canada have impacted nearly 20 million ha of pine forest during their recent epidemic outbreak, which began in the 1990's, and are projected to continue infesting boreal forests as they move eastward (Dhar et al., 2016). Insect and diseases have also affected a much greater area than fires in North American temperate forests during 2003–2012 (van Lierop et al., 2015). Climate change is expected to increase the frequency of forest disturbances for a number of reasons, acting on both biological agents and abiotic disturbances (Ayres and Lombardero, 2000; Ramsfield et al., 2016; Weed et al., 2013). One of the most powerful ecological interactions in the boreal forest, similar to temperate regions, are disturbances coupled with on-going drought. By further stressing a system with a disturbance during an ongoing drought, the severity of the interactions can be intensified and the future health of the forest compromised if threshold levels are exceeded (Millar and Stephenson, 2015). Though a natural feature of boreal forest dynamics, increased forest disturbances under climate change could have strong negative impacts on timber supply.

4.1. Biotic disturbances

Insects in the boreal forest are likely to benefit from climate change due to i) lower winter mortality rates (milder temperatures) and ii) lower resistance in trees from temperature and moisture stress (Weed et al., 2013). A tree's resistance to defend itself against insect and/or pathogen attack is lowered from drought and higher temperature (Kurz et al., 2008; Millar and Stephenson, 2015). As a result of these interactions, we are likely to see more widespread and devastating insect infestations in northern forests (Pureswaran et al., 2015). Though a slight decrease frequency in spruce bud worm has been forecasted due to the reduction in suitable hosts (Candau and Fleming, 2011). An increased insect (*Ips* spp. beetles) susceptibility has been forecasted in Austria and has already occurred in Lithuania and Canada (mountain pine beetle) (Alfaro et al., 2009; Ozolincius, 2012; Seidl et al., 2008). Insect outbreaks in Russia appear less studied than elsewhere, though reports indicate that silk moth (a major disturbance agent) has increased substantially over the last 20 years (Schaphoff et al., 2016). The effects of fungal tree diseases under climate change are less predictable, as there have been mixed results in studies; there could be increases in particular pathogens and reduced impacts from others (Pautasso et al., 2015). For the boreal forest, it is anticipated that diseases and insects will spread due to increasing temperatures and possibly have new species introduced through global trade (Pautasso et al., 2015; Pecl et al., 2017; Sturrock, 2012). Though pest and pathogen disturbances may increase in frequency through improved climate conditions, drought events assist in determining which pest could inflict the most damage by influencing the section of the tree that insects and fungi target (e.g., foliar versus woody) depending on drought severity and method of pest damage (Jactel et al., 2012). Generally, as the severity of droughts increase, infestation by certain pests will be favoured in alignment with their mode of damage (e.g. wood borers performed best on drought stressed trees).

4.2. Abiotic disturbances

Fires are projected to increase in frequency and intensity under climate change, due to higher temperatures, decreased precipitation and longer fire season over many areas (Flannigan et al., 2005; Moritz et al., 2012). The potential area burned annually could increase dramatically in Canada (Boulanger et al., 2014; Girardin et al., 2009) and eastern Russia with continued dry conditions (Groisman et al., 2007). Greater quantities of dead wood from fungal mortality and insect infestations provide greater fuel availability for fires, increasing the likelihood of severe burns (Flannigan et al., 2009; Gillett et al., 2004). Drought and warmer conditions potentially cause greater tree mortality, which further increase the fuel available for fire ignition (Ruthrof et al., 2016). More frequent storms are expected with new weather patterns under changing climate, increasing the probability of lightning strikes igniting a fire (Flannigan et al., 2009; Shvidenko and Schepaschenko, 2014). However, it has been suggested that fire frequency and intensity could be lowered, in certain areas, as a result of greater deciduous tree species composition since they are less flammable (Terrier et al., 2013). It is necessary to consider tree species when evaluating the vulnerability of forests to fire; North America and Eurasia have different dominant tree species, which results in a contrasting level of high intensity crown fires versus lower intensity fires (Rogers et al., 2015). Though there exist areas less prone to fire (e.g., larch and spruce swamps) that have much longer fire return intervals (Johnson, 1992). The risk of increased fire to timber supply in the boreal forest across Canada is generally low in many regions (Girardin et al., 2009); however, vulnerability increases with higher temperatures and lower precipitation in the future (Gauthier et al., 2015b). Other disturbances include storm related events such as wind throw, which may increase in severity and frequency due to stressed and weakened trees (Blennow et al., 2010; Girard et al., 2014; Peltola et al., 2010), coupled with more

frequent climate extremes (IPCC, 2014).

5. Growth, mortality, and composition in established forest stands

Identifying trends in growth, mortality and species compositional shifts within local stands is necessary for gaining a clear understanding of the impacts of climate change on timber availability. Timber volume, or biomass, that is available for harvest represents the accumulation of net growth (growth minus mortality), while species composition reflects the types of timber, an aspect of timber quality, that are available for harvest.

5.1. Growth and mortality

Tree growth can be quantified at both the individual tree and stand levels, and described in a variety of ways, through increasing: size, biomass, gross primary production (GPP, the total amount of carbon accumulated from photosynthesis), or net primary productivity (the difference between GPP and plant respiration) (Luyssaert et al., 2007). We will focus on tree growth in terms of increasing size or biomass accumulation because both relate to volume (Chojnacky et al., 2013). Growth in northern regions typically improve as they warm, in contrast to dryer southern areas (Boisvenue and Running, 2006; D'Orangeville et al., 2016). However, there are instances of the opposite occurring (Table 1) (Boisvenue and Running, 2006; Luyssaert et al., 2007; Zhao and Running, 2010). Rising atmospheric CO_2 concentrations may have contributed to improved tree growth more than temperature at the stand level (Brienen et al., 2015; Chen et al., 2016), though it is unclear which factor is most influential in the boreal as it is difficult to partition their effects (Girardin et al., 2016a; Price et al., 2013). Further, growth may fluctuate quickly in forests due to annual variations in temperature and precipitation (Pretzsch et al., 2014; Toledo et al., 2011). Throughout Europe, *Picea abies* (Norway spruce) has experienced greater growth rates, stand volumes and stock accumulation over the last 100 years because of changing climate (Pretzsch et al., 2014; Schlyter et al., 2006). Individual tree growth rates in eastern Canadian boreal tree species are expected to increase with climate change (Huang et al., 2013), though significant spatial variations in historical growth rates show no collective growth gain across the landscape (Girardin et al., 2016a). However, evidence of increased local growth rates have been shown both in simulation scenarios (Bergh et al., 2003; Nabuurs et al., 2002), and in historical/ observational studies in certain areas (Kauppi et al., 2014; Pretzsch et al., 2014). In western Canada though, increased tree growth tends to be restricted to young stands (Chen et al., 2016) and/or broadleaf dominated stands (Chen and Luo, 2015). Coupled with rising CO_2, global warming with longer growing seasons (Boisvenue and Running, 2006; Linderholm, 2006) could be attributable to the observed increase in tree growth (Table 1).

Decreases in available climate moisture lead to droughts that lower the growth rate and raise mortality in forests (Table 2) (Bennett et al., 2015). Drought can be observed as an event, such as particular years of severely decreased precipitation, or as a general reduction of moisture in the area over time from changes in precipitation regimes (Dai, 2011). Drought is possibly the single most influential factor in the growth of trees (Fig. 2) (Allen et al., 2010b; Anderegg et al., 2013). Studies reporting increased tree mortality and/or declines in growth often cite drought as the primary factor (Barber et al., 2000; Ciais et al., 2005; Zhao and Running, 2010). Trees require more water under higher temperatures in order to meet evapotranspiration demands but are unable to meet these requirements under drought conditions (Peng et al., 2011; van Mantgem et al., 2009). What is even more concerning, in relation to the forest industry, is that drought has been shown to cause greater rates of mortality in larger diameter trees (Bennett et al., 2015). This is a contested point, however, with different methodologies yielding contrasting evidence concerning the susceptibility of trees to drought based on their height (Greenwood et al., 2017; Hember et al., 2017). In boreal forests, after properly accounting for the increased tree mortality probability with stand ageing (Luo and Chen, 2011), Luo and Chen (2013) demonstrated that climate change-induced tree mortality is greater in young stands than in older stands. More importantly, even without reduced climate moisture availability, tree mortality increases with climate change in boreal and other biomes (Brienen et al., 2015; Luo and Chen, 2015), which were attributable to: reduced tree longevity, increased competition and/or direct heat stress associated with global warming (Allen et al., 2015). Other mechanisms, including hydraulic failure, carbon starvation, greater susceptibility to biotic disturbances, and increased losses of nutrients, could also contribute to widespread increases in tree mortality worldwide (Allen et al., 2010b; Brienen et al., 2015; Houle et al., 2016; Rowland et al., 2015). Global warming coupled with continued drought occurrence could remove significant harvestable volumes from the boreal forest.

While intergovernmental reports demonstrate the increasing severity of droughts in the world (IPCC, 2014), the future of drought in the boreal forest is largely uncertain due to varying reports that differ in data sets and drought indices used, as well as the unpredictability of future events (Trenberth et al., 2013). For example, historically similar total amounts of precipitation may fall in two areas but with different frequencies and individual amounts (Dai, 2012; Trenberth et al., 2013). Annual precipitation levels may be identical, but droughts may occur between rain events, or a higher proportion of precipitation may fall as snow. Though there are conflicting reports of future droughts, they are likely to become more frequent in certain areas due to increased temperatures and varying precipitation regimes, making forests more vulnerable (Allen et al., 2015; Dai, 2012). It is important to note that although climate change may increase tree growth in some cases, studies that simultaneously examined growth and mortality in response to climate change have shown that aboveground biomass loss is far greater than biomass gain from increased growth, reducing net growth in both boreal and tropical forests (Brienen et al., 2015; Chen and Luo, 2015; Chen et al., 2016). This indicates that, overall, climate change has reduced biomass or timber volume available for harvest. Ongoing climate change with more warming and drought might further reduce timber volumes available due to high mortality losses.

5.2. Composition shifts

In general, tree species respond to climate change differently (Drobyshev et al., 2013). As temperature regimes shift, northern latitudes may have unsuitable environments for certain species (Perie and de Blois, 2016). In the event that regional average temperatures exceed 2 °C, deciduous broadleaf trees are expected to become more dominant in Russia, whereas conifers may regress (Schaphoff et al., 2016). In Canada, *Picea mariana* (black spruce) populations have declined due to increased temperatures, making northeastern locations more suitable for their growth because of greater precipitation (D'Orangeville et al., 2016; Girardin et al., 2016b). More frequent drought occurrences favour, or have lesser impacts, on drought tolerant species such as *Pinus* spp. (Anderegg et al., 2013; Chen and Luo, 2015; Luo and Chen, 2015).

The increased frequency of disturbance regimes may also impact species available for harvest. Those species that are less adapted to disturbance, such as later successional species, would likely be pushed out of heavily disturbed areas in favour of more tolerant or faster growing pioneer species (Chen et al., 2009; Johnstone et al., 2010). Among pioneer species, vegetatively reproducing *Populus* and *Betula*, are likely better at colonizing heavily disturbed sites (Chen et al., 2009; Ilisson and Chen, 2009; Price et al., 2013), though deciduous trees do not thrive in areas of severe drought (Michaelian et al., 2011). Moreover, in established forest stands without stand replacing disturbances, climate change has also shifted species composition toward a greater proportion of early successional species such as *Pinus, Populus* and *Betula* at the expense of *Picea* and *Abies* in western boreal forests of Canada (Searle and Chen, 2017).

Table 1
Global and boreal evidence of variation in growth productivity as a result of climate change (positive influence of climate change, negative influence, and reports of mixed findings).

Positive	Study area	Methods	Findings	Causes
Bergh et al. (2003)	Scandinavia	Growth model simulations	Increased growth, provided water not limited	Longer growing seasons
Berner et al. (2013)	NE Siberia	Satellite and tree ring data	Productivity influenced by seasonal temp. and moisture	Response varies seasonally, warmer temp. and enough precip. needed
Boonstra et al. (2008)	NW Canada	Tree ring data	Higher temperatures increased growth as did the fertilizer	Cold and nutrient deprived region
Luyssaert et al. (2007)	Global	Global carbon flux database	Biomass accumulation in boreal is slower than global average	Saturation point of 10 °C and 1500 mm
Kauppi et al. (2014)	Finland	National Forest Inventory permanent sample plots	Growth rates increased	Longer growing seasons
Nabuurs et al. (2002)	Europe	Process based forest growth simulation	Net annual increments increased in response to climate changes	Large uncertainty surrounding future ecological changes
Pretzsch et al. (2014)	Central Europe	Long term plot sampling	Climate change increases growth rates and stand volume	Favorable climate conditions
Sato et al. (2016)	E Siberia	Simulation model	Increase in larch forest growth	More growing days, constant moisture
Ciais et al. (2008)	Europe	NFI and timber harvest statistics	Biomass accumulation increased	Increase in net primary production
Negative	Study area	Methods	Findings	Causes
Aakala and Kuuluvainen (2011)	NW Russia	Tree ring sampling	Reduced tree growth	Drought conditions
Beck et al. (2011)	Alaska	Satellite and tree ring data	Decline in southern productivity	Hydraulic limitations from high vapor pressure deficits
Chen and Luo (2015)	W Canada	Forest inventory permanent sample plots	Net biomass declines	Tree mortality outpaces growth
Chen et al. (2016)	W Canada	Forest inventory permanent sample plots	Net biomass declines in older stands	Less productivity in older stands
Luo and Chen (2015)	W Canada	Permanent sample plots	Biomass losses even when water is not limited	Competition
Barber et al. (2000)	Alaska	Tree sampling and ring data	Decreased growth of white spruce	Heat and drought
Girardin et al. (2016b)	Canada	Tree ring data in (climate) carbon model	Loss of black spruce productivity	Higher temperatures
Ge et al. (2010)	Finland	Integrated process-based model	Lower stem volume production	Drought and less nutrients
Ciais et al. (2005)	Europe	Eddy covariance	Decrease in productivity in European forest	High temperature
Zhao and Running (2010)	Global	Satellite imaging and drought index	Reduced global NPP-may have increased short term NPP in northern regions	Drought stress and continued drying from high temp.
Montwe et al. (2016)	W. Canada	Provenance trials	Northern seed sources' growth depressed	Not adapted to drought conditions
Mixed	Study area	Methods	Findings	Causes
Boisvenue and Running (2006)	Global	Literature review	Increases and decreases in productivity, greater changes in northern areas	Longer growing season, need adequate water
Lloyd et al. (2011)	Siberia	Tree ring analysis	Better growth in north than south	Different responses to temp. and precip.
Sitch et al. (2008)	Global	Climate carbon model and Dynamic Global Vegetation Model	Forests either sources or sinks in future: boreal projected to lose forest area	Various climate inputs based on scenarios
Ge et al. (2011)	Finland	Process based ecosystem model	Better growth in north than south	Different responses to temp. and precip based on species and latitude
Girardin et al. (2012)	Canada	Plot level tree growth analysis	Heterogeneous growth responses between species and demographics	Areas with more growth may not exceed the added mortality and site stresses
Huang et al. (2013)	Canada	Tree ring data and modeling	Better growth in north than south boreal	Temperature increase less severe in northern areas promoting growth
D'Orangeville et al. (2016)	Canada	Tree ring analysis	Latitude and climate constrain growth	Different responses to temp. and precip.
Peñuelas et al. (2011)	Global	Tree ring isotopic and growth data	Enhanced water use from higher air CO_2 didn't always lead to better growth in boreal regions	Other factors restrained growth

Table 2
Global studies with boreal implications and boreal specific evidence of tree mortality as a direct result of drought from climate change.

Mortality evidence	Study area	Type	Methods	Results
Allen et al. (2010a)	Global	Review	Literature synthesis	Increased tree mortality both globally and in boreal regions
Allen et al. (2015)	Global	Review	Literature synthesis	Droughts have profound impact with high temp. Though uncertain future in boreal
Anderegg et al. (2013)	Primarily NA	Review	Literature synthesis	Increase tree mortality impacts ecosystem functions and services, post mortality recovery takes decades in boreal settings
Barber et al. (2000)	NW USA	Article	Tree ring sampling	Depressed growth from drought
Ciais et al. (2005)	Europe	Article	Eddy covariance	Increase tree mortality and more profound drought effect with high temp.
Clark et al. (2016)	USA	Review	Literature	Drought intolerant boreal/temperate species replaced by tolerant temperate
Dai (2011)	Global	Review	Drought indices	Severe drought occurrences generally expected globally most boreal regions may have adequate precip.
Hember et al. (2017)	NA	Article	PSP data, climate data and mortality modeling	Water-stressed tree mortality not likely increasing with tree size
Houle et al. (2016)	E. Canada	Article	Nutrient and precipitation sampling	Decreased site quality from nutrient loss through drought
Michaelian et al. (2011)	SW. Canada	Article	Monitoring plots	Increase tree mortality from drought
Peng et al. (2011)	Canadian Boreal	Article	Permanent sample plots	Increase tree mortality from drought
Trenberth et al. (2013)	Global	Review	Literature synthesis and comparison	Disparity in conclusions drawn on the future of drought, data bias in northern areas

6. Implications to boreal forestry

Climate change influences the quantity and quality of boreal forest timber supply in different ecological ways, particularly in the three ways discussed above. Biome shifts highlight a disparity between southern forest mortality and northern forest migration rates. Northern forests are not migrating fast enough to keep up with favorable climate zones (Aitken et al., 2008), nor are they adapted to new southern boreal climate conditions (Allen and Breshears, 1998). This may lead to reductions in overall productive boreal forest growing area due to the mismatch between the two (Anderegg et al., 2013; Hanewinkel et al., 2013; Tchebakova et al., 2016). Rapid climate change over the next century will likely intensify this problem (Donoghue and Edwards, 2014). Reduced productive forest area has major implications to future timber supply and the forest industry. Since temperatures are higher along the southern edges of the boreal, where negative effects of climate change are most pronounced (D'Orangeville et al., 2016), forestry operations may see significant alterations in harvestable volumes and species compositions (Hanewinkel et al., 2013).

Ongoing climate change contributes to the increasing frequency and intensity of biotic and abiotic disturbances in the boreal forest, and are factors in decreasing harvestable timber volumes (van Lierop et al., 2015). This will occur as a combination of insect, pathogen (Weed et al., 2013) and fire disturbances (Flannigan et al., 2005), which are compounded by regional drought events (Allen et al., 2015; Millar and Stephenson, 2015). Risk averse managers should account for disturbances, particularly fire, when forecasting timber supply impacts especially in vulnerable areas (Savage et al., 2010). Additionally, by changing the age class structure of the forest through shortened disturbance intervals, forest managers will have a more difficult time supplying mills with mature, harvestable wood (Gauthier et al., 2015b; McKenney et al., 2016; NRTEE, 2011).

Growth rates at the stand level are expected to increase in areas not limited by decreased moisture availability because of rising CO_2 levels, warmer temperatures with longer growing seasons (Boisvenue and Running, 2006), and being situated in northern locations (Ge et al., 2011; Kellomäki et al., 2008). Increased growth, however, does not necessarily result in improved timber volumes (Tian et al., 2016) if mortality losses are greater than growth gains (Chen and Luo, 2015; Chen et al., 2016). Growth trends associated with climate change seem region and site specific, but generally with the historical limiting growth factor shifting from low temperature to low moisture levels in warmer northern areas (Berner et al., 2013; Charney et al., 2016). Across the boreal biome, some areas have become more productive while others less so, collectively canceling each other out (Girardin et al., 2016a). Because increased tree mortality is projected to outpace increased growth, accompany no growth gain or even reduced growth (Chen and Luo, 2015; Chen et al., 2016), the net effect of climate change on biomass and timber production is negative in established forests (Reyer et al., 2017). These results differ considerably from most published articles on the topic of climate change and timber supply (Table 3) (Tian et al., 2016) and reviews examining climate change

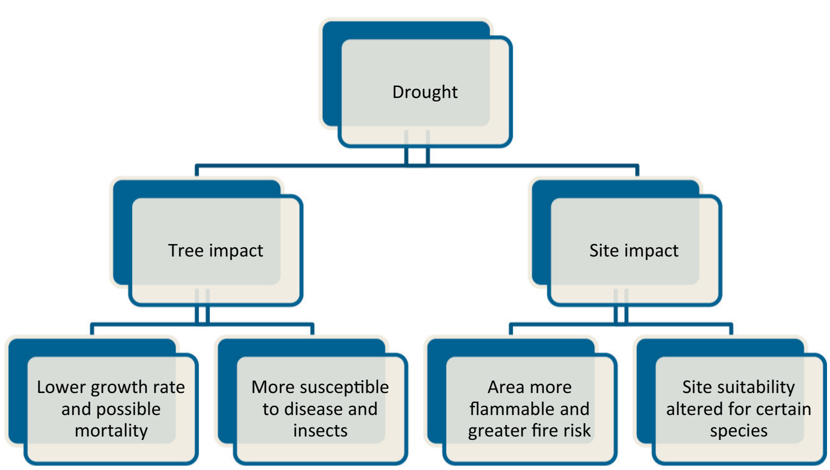

Fig. 2. Some of the many impacts of drought in a boreal forest stand. Drought can both affect the site by making it dryer and the trees by stressing them. There are four possible end results during a drought occurence that are described.

Table 3
Summary of timber modeling studies with reference to forestry implications and the effect on economic areas.

Area	Year	Methods	Results	Impact to forestry	Economic implications
Global[1]	2016	Climate data from the MIT Integrated Global Systems Model in a DGVM. NPP and die back are then used in an updated Global Timber Model (GTM).	Increases in global NPP in both temperate and tropical forests, though increases in dieback occur as well. Timber increases resulting in decreased global timber prices.	Advantage	Timber prices
Global[2]	2001	Climate data from two climate intensity models used in BIOME3 for tree species distribution and productivity. GTM then maximizes NPV of forests from outputs	Increases in NPP globally but with high variance in timber losses. Timber supply increases leads to lower timber prices. Most change occurs in inaccessible boreal regions.	Advantage	Timber prices
Global[3]	2002	Used Terrestrial Ecosystem Model to derive CO_2 data to modify timber supply in a GTM. This will then show market implications for fluctuations in timber resources.	Timber increases lead to economic benefits with lower global timber prices. Market analysis found greater consumption of wood products despite some product surplus.	Advantage	Gross domestic product
Europe[4]	2013	Developed a biome shift model through regionalized GCMs and NFI. Cash flows are generated through timber growth simulator for use in LEV calculations identifying the change in European forest value.	All climate scenarios resulted in less Norway spruce dominated land (migrated north) indicating a loss in land and timber value. New climate benefitted oak and pine.	Disadvantage	Land expectation value
Canada[5]	2012	Used a CGE model to assess the economic impact of climate change on Canadian forests. Computed results based on varying scenarios.	Results generally show negative impacts to economy, though with high variances. Shows the importance of forestry adaptations to benefit the economy.	Both	Canadian economy
Global[6]	2000	Utilize a Global Impact Model (GIM) that combines future world scenarios, climate simulations, sectoral data, market sector response to climate change. Based on three scenarios from the IPCC	Small increases in global GDP in year 2100 under climate scenarios. Forestry market is expected to increase in wealth from increased forest productivity- primarily boreal.	Advantage	Global GDP
Europe[7]	2003	Used a regionalised, partial equilibrium model (EFI-GTM) to model profit maximizing in the European forest market. Analysed accelerated forest growth in a variety of scenarios for a variety of products.	Increased wood production within Europe leads to lower prices and less importing in most scenarios. Lower wood prices compromise producer incomes. Logs and sawn wood are products most affected.	Both	Timber prices
Russia[8]	2013	Studied the combined use of an ecological gap model and economic model in Russian forests as temperatures increase over the next 90 years	Found general increases in timber yields at 2 °C warming but general decreases in timber yield and carbon sequestration at 4 °C depending on site location and species	Both	Carbon pricing

1-(Tian et al.); 2-(Sohngen et al.); 3-(Perez-Garcia et al.); 4-(Hanewinkel et al.); 5-(Ochuodho et al.); 6-(Mendelsohn et al.); 7-(Solberg et al.); 8-(Lutz et al.)

impacts on boreal forest productivity (Kirilenko and Sedjo, 2007; Price et al., 2013).

The quality of timber supply is determined not only by age structure available for harvest (Gauthier et al., 2015b; NRTEE, 2011), but also the availability of certain tree species. Coupled with more frequent disturbances, an increased abundance of deciduous broadleaf species are reproducing at the expense of late-successional conifers (Chen and Taylor, 2012; Ilisson and Chen, 2009; Johnstone et al., 2010). In addition, species compositions in established forests are shifting to lower abundances of late successional spruce and fir (Searle and Chen, 2017), and may continue to decrease further over time (Kellomäki et al., 2008). A greater proportion of early successional species may benefit a portion of forest industry that utilizes aspen, and especially pine, however later-successional conifers are generally preferred in pulp/paper and lumber. This shift in composition may allow for the development of new wood industry products if a company's financial constraints are flexible enough to adapt to changing forest supply. Simultaneously, increased growth rates in softwood species actually decreases their mechanical properties, such as density and strength (Zhang, 1994), because the growth rings are spread farther apart with a lower proportion of latewood to early wood (Zhu et al., 2007). By reducing mechanical properties and skewing species composition toward less favorable options, wood quality and the value of the forest may be lessened through climate change.

As the references in Table 3 show, conflicting understandings of climate change impacts to forestry exist. Many of the older studies show benefits to forest industry stemming from increased growth and forest expansion (Mendelsohn et al., 2000; Sohngen et al., 2001). In some cases, economic benefits are not realized because of the flood of timber into the market lowering prices (Perez-Garcia et al., 2002; Solberg et al., 2003) or because additional temperature increases caused productivity declines (Lutz et al., 2013). In the cases of negative forestry impacts, studies showing reductions in boreal forest area (Hanewinkel et al., 2013) or increases in forest disturbances (Reyer et al., 2017; Tian et al., 2016) result in lowered available timber. The total economic implications of reduced timber are complex but a major factor is how dependent a region's economy is on forestry (Ochuodho et al., 2012).

The forest industry requires a consistent and predictable supply of timber in order to have viable operations. However, climate change will affect forestry operations in managed forest areas. This can include earlier ground thaw with a shorter winter harvest, and more frequent extreme weather (heat, rain and snowmelt duration) making fieldwork more dangerous (Rittenhouse and Rissman, 2015). Changes in weather patterns impact forest companies through: inaccessibility to forestland from flooding, more frequent and higher costs on road repair, and damage to timber from snow, ice, or storms (DeWalle et al., 2003). These factors have important implications since winter harvesting of wetlands (spruce forests) may be shortened, while more frequent storms may impact the quality of the timber and structure of forest roads (Lempriere et al., 2008). This is an important scenario since one of the greatest costs in boreal forestry is the construction and maintenance of roads. Higher moisture conditions from warmer winters and continued snow melt can lead to increased export of mercury and organic matter from the site if driven on by vehicles, causing environmental damage (Keskitalo et al., 2016). As climate continues to change, management may also be hard pressed to meet sustainability and conservation objectives (Gauthier et al., 2014). To continue having a profitable and successful forest industry, adapting management to the impacts of climate change is essential.

7. Adaptations to the uncertainties of 21st century climate change

Management is vital to maintaining efficient biomass production in the boreal forest (Campioli et al., 2015) and this will only continue under climate change through adaptation. Adaptation is needed to continue receiving benefits from the environment, and the value of

adaptations needs to be expressed to society (Guo and Costello, 2013). Adaptations can either be reactive or proactive; proactive modifications are most favorable as they reduce exposure to risk, though more often reactive adaptations are used in forestry practices (Gauthier et al., 2014). Intensive treatments through behavioral changes, or extensive treatments that apply discrete adaptations, are further strategies (Guo and Costello, 2013). It is important to recognize that adaptive measures should be implemented based on context, not applying the same action to all situations (Gauthier et al., 2014). Several papers have proposed comprehensive recommendations for climate change adaptations (Hisano et al., 2018; Park et al., 2014). Here we focus on how adaptations may proceed in response to biome shifts, increased disturbances, reduced net growth and compositional shifts.

Shifting biomes and climate envelopes present new challenges to forest industry; provenance trials have demonstrated that southern populations are declining while northern ones are benefiting from warmer climate (Pedlar and McKenney, 2017; Thomson and Parker, 2008). As climate is altered, plant species may form isolated populations (Pearson, 2006), adapt to local conditions or hybridize to survive under new climate conditions (Aitken et al., 2008). Assisted migration, therefore, may be utilized as a way ensure species are growing under optimal climate conditions (Aitken et al., 2008; Gauthier et al., 2014). This means not only migrating current (local) seed sources north, but also bringing southern species/ seed sources northward to cope with dryer and warmer conditions (Keskitalo et al., 2016; Thomson and Parker, 2008). To ensure that currently harvested and planted forests will be sustainably productive again in the future, they must be managed to succeed in a changing climate (Lempriere et al., 2008; Park et al., 2014). However, we do not yet fully know the implications of moving seed sources or southern species into northern locations.

Every year, large areas of forest land are impacted by forest disturbances (van Lierop et al., 2015), which affects the harvestable volumes from the region. In order to protect valuable mature stands, certain measures can be taken in susceptible regions; namely the management of fires and pests (NRTEE, 2011). This may be accomplished through fire suppression and pesticide applications; though in the case of fire, future costs may increase drastically and impede fire management (Hope et al., 2016). When affected by a disturbance, salvage harvesting is a method sometimes employed but can lead to complications in the milling process (Lempriere et al., 2008), as well as nutrient removal with implications for long-term site productivity (Hume et al., 2018). Although, salvage harvesting can recover some of the lost timber (Leduc et al., 2015; Seidl et al., 2008), it is always better to protect areas proactively (before salvaging is necessary), to avoid negative economic impacts (NRTEE, 2011; Ochuodho et al., 2012).

In monoculture conifer stands, hardwoods could be added to the composition to increase functional diversity, possibly helping to mitigate the impacts of climate change (Hisano et al., 2018) and improve productivity (Liang et al., 2016). Though not necessarily increasing harvestable volumes, mixed-woods do provide lower risk both financially and industrially, since they are more resistant to abiotic and biotic disturbances and are better able to recuperate afterwards (Hisano et al., 2018; Knoke et al., 2007; Zhang et al., 2012). Also, designing forests with greater adaptive capacity will delay the negative aspects of climate change (Park et al., 2014). As a result of altered species compositions, manufacturers may subsequently have to adapt new wood products to changing supply demographics, though at a greater expense (Lempriere et al., 2008).

8. Summary and future directions

Climate change affects ecological processes at different spatial scales and impacts timber supply in boreal forests. First, the area of productive boreal forest may decrease as northern migration rates are slower than the speed at which southern limits retreat from unfavourable climate conditions. Second, forest disturbances have increased in recent decades and are anticipated to increase in severity and/or frequency, leading to younger forest age structures and increased dominance of early successional tree species over late-successional species. Third, tree growth in established forests has increased in areas where water availability is not limiting as the result of warmer temperatures, longer growing seasons and CO_2 fertilization. However, widespread increases in tree mortality have occurred over the last several decades due to direct heat stress, drought and increased disturbances. Increased mortality has occurred at a greater rate than growth increases, or has accompanied reduced growth rates, leading to decreased net growth and net volumes. Moreover, late successional tree species are more vulnerable to climate than early successional species in established forests, leading to the increased dominance of early successional conifers and broadleaves. These trends are expected to continue as warming and extreme weather conditions are anticipated to be amplified in the 21st century.

Changes in timber quantity and quality have profound impacts on the forest industry. First, lower net harvestable volumes will likely be available since climate change induced mortality losses are greater than growth gains. Second, product manufacturing will need to accommodate new supply demographics, though it is costly to alter processing facilities; despite this, new unforeseen opportunities may arise. Third, locating sufficient mature timber may become more difficult as increased disturbances skew the forest age structure to younger levels. Lastly, the overall quality of extracted wood is likely to decline since there will be greater impact from disturbances and greater proportion of less desirable species. However, once again, this may offer a new range of opportunities for specific niches in product manufacturing. Additionally, even if there are fewer disturbance events at a given site, accelerated growth rates can lead to lower quality softwood timber because of decreased mechanical wood properties.

Therefore, adaptations in the forestry sector are needed to keep the industry viable and sustainable during this time of change. Certain adaptations are more applicable in areas over others; thus, careful planning, and in some cases new policy, is necessary. Management adaptations include: assisted migration into favorable growing areas, fire and pest management to protect mature stands, and improving resilience and adaptive capacity to disturbances by enhancing forest diversity. Innovation and research will be necessary to better understand the full scope of their consequences and to improve our understanding of future timber supply.

Continued research is required to properly assess the future impacts of climate change; there is still much uncertainty. To conclude, we propose four areas of future research.

(1) It is known that boreal forests are shifting northward, yet this may differ regionally depending on climate moisture availability (Fei et al., 2017). More knowledge of species specific responses is required; the continued study of provenance trials could provide a wealth of information (Pukkala, 2017). Further, more definitive rates of decline in southern boreal limits and rates of expansion in northern limits are needed since there exist many conflicting estimates (Chen et al., 2011). Better understanding this will provide information on the productive forest area available to industry in the future, which has been suggested to be decreasing (Hanewinkel et al., 2013). Repeatedly measured satellite imagery may likely assist in accurately determining forest migration rates (Hofgaard et al., 2013).
(2) Boreal forest wildfires are expected to increase in the future (Flannigan et al., 2009) but can differ considerably among boreal forest regions (Girardin et al., 2013). We need to better understand how younger, fire-origin forests feedback into wildfire regimes (Boulanger et al., 2017). It is also necessary to improve our understanding of the changing relative importance of different disturbance types under on-going climate change, and its spatial variations (Hansen et al., 2013; Logan et al., 2003). Our knowledge is

also limited concerning the development of future forest diseases; it is unclear what role they will play in conjunction with forest dynamics and other disturbances.

(3) Efforts have been made to study the impacts of climate change on net forest biomass accumulation in western Canadian boreal forests (Chen and Luo, 2015; Chen et al., 2016). However, there has been little research done on this topic in other regions. As well, there is no clear understanding of how large scale mortality will affect the succession of tree species compositions (Anderegg et al., 2013). Compositional shifts of tree species are important to forest industry. While observational (Searle and Chen, 2017) and simulation (Shuman et al., 2015) studies have shown that climate change induces compositional shifts to early successional tree species in western Canada and Russia, it remains unclear whether this trend is pan-boreal.

(4) It is important to determine the economic and societal consequences of changes in the boreal forest. Intensively managed areas, providing economic benefits, may respond differently to climate change than unmanaged forests, prompting continued study. As well, previous results based on simulation studies (Perez-Garcia et al., 2002; Sohngen et al., 2001) generally differ from the empirical evidence that we have synthesized. There is a need to reconcile this disparity to clearly inform policy makers and forest managers.

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References

Aakala, T., Kuuluvainen, T., 2011. Summer droughts depress radial growth of Picea abies in pristine taiga of the Arkhangelsk province, northwestern Russia. Dendrochronologia 29, 67–75.
Aitken, S.N., Yeaman, S., Holliday, J.A., Wang, T., Curtis-McLane, S., 2008. Adaptation, migration or extirpation: climate change outcomes for tree populations. Evol. Appl. 1, 95–111.
Alfaro, R.I., Campbell, E., Hawkes, B., 2009. Historical Frequency, Intensity, and Extent of Mountain Pine Beetle Disturbance in British Columbia. Natural Resources Canada, Canadian Forest Service.
Allen, C.D., Breshears, D.D., 1998. Drought-induced shift of a forest–woodland ecotone: rapid landscape response to climate variation. Proc. Natl. Acad. Sci. 95, 14839–14842.
Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., et al., 2010a. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manag. 259, 660–684.
Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., et al., 2010b. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manag. 259, 660–684.
Allen, C.D., Breshears, D.D., McDowell, N., 2015. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anhropocene. Ecosphere 6, 1–55.
Anderegg, W.R.L., Kane, J.M., Anderegg, L.D.L., 2013. Consequences of widespread tree mortality triggered by drought and temperature stress. Nat. Clim. Chang. 3, 30–36.
Ayres, M.P., Lombardero, M.J., 2000. Assessing the consequences of global change for forest disturbance from herbivores and pathogens. Sci. Total Environ. 262, 263–286.
Barber, V.A., Juday, G.P., Finney, B.P., 2000. Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. Nature 405, 668–673.
Beck, P.S., Juday, G.P., Alix, C., Barber, V.A., Winslow, S.E., Sousa, E.E., et al., 2011. Changes in forest productivity across Alaska consistent with biome shift. Ecol. Lett. 14, 373–379.
Bennett, A.C., McDowell, N.G., Allen, C.D., Anderson-Teixeira, K.J., 2015. Larger trees suffer most during drought in forests worldwide. Nat. Plants 1, 15139.
Bergh, J., Freeman, M., Sigurdsson, B., Kellomäki, S., Laitinen, K., Niinistö, S., et al., 2003. Modelling the short-term effects of climate change on the productivity of selected tree species in Nordic countries. For. Ecol. Manag. 183, 327–340.
Berner, L.T., Beck, P.S.A., Bunn, A.G., Goetz, S.J., 2013. Plant response to climate change along the forest-tundra ecotone in northeastern Siberia. Glob. Chang. Biol. 19, 3449–3462.
Blennow, K., Andersson, M., Sallnäs, O., Olofsson, E., 2010. Climate change and the probability of wind damage in two Swedish forests. For. Ecol. Manag. 259, 818–830.
Boisvenue, C., Running, S.W., 2006. Impacts of climate change on natural forest productivity - evidence since the middle of the 20th century. Glob. Chang. Biol. 12, 862–882.
Boonstra, R., Desantis, L., Krebs, C.J., Hik, D.S., 2008. Climate and nutrient influences on the growth of white spruce trees in the boreal forests of the Yukon. Clim. Res. 36, 123–130.
Boulanger, Y., Gauthier, S., Burton, P.J., 2014. A refinement of models projecting future Canadian fire regimes using homogeneous fire regime zones. Can. J. For. Res. 44, 365–376.
Boulanger, Y., Girardin, M., Bernier, P.Y., Gauthier, S., Beaudoin, A., Guindon, L., 2017. Changes in mean forest age in Canada's forests could limit future increases in area burned but compromise potential harvestable conifer volumes. Can. J. For. Res. 47, 755–764.
Brienen, R.J., Phillips, O.L., Feldpausch, T.R., Gloor, E., Baker, T.R., Lloyd, J., et al., 2015. Long-term decline of the Amazon carbon sink. Nature 519, 344–348.
Campioli, M., Vicca, S., Luyssaert, S., Bilcke, J., Ceschia, E., Chapin Iii, F.S., et al., 2015. Biomass production efficiency controlled by management in temperate and boreal ecosystems. Nat. Geosci. 8, 843–846.
Candau, J.N., Fleming, R.A., 2011. Forecasting the response of spruce budworm defoliation to climate change in Ontario. Can. J. For. Res. 41, 1941–1960.
Charney, N.D., Babst, F., Poulter, B., Record, S., Trouet, V.M., Frank, D., et al., 2016. Observed forest sensitivity to climate implies large changes in 21st century North American forest growth. Ecol. Lett. 19, 1119–1128.
Chen, H.Y., Luo, Y., 2015. Net aboveground biomass declines of four major forest types with forest ageing and climate change in western Canada's boreal forests. Glob. Chang. Biol. 21, 3675–3684.
Chen, H.Y.H., Taylor, A.R., 2012. A test of ecological succession hypotheses using 55-year time-series data for 361 boreal forest stands. Glob. Ecol. Biogeogr. 21, 441–454.
Chen, H.Y.H., Vasiliauskas, S., Kayahara, G.J., Ilisson, T., 2009. Wildfire promotes broadleaves and species mixture in boreal forest. For. Ecol. Manag. 257, 343–350.
Chen, I.C., Hill, J.K., Ohlemuller, R., Roy, D.B., Thomas, C.D., 2011. Rapid range shifts of species associated with high levels of climate warming. Science 333, 1024–1026.
Chen, H.Y., Luo, Y., Reich, P.B., Searle, E.B., Biswas, S.R., 2016. Climate change-associated trends in net biomass change are age dependent in western boreal forests of Canada. Ecol. Lett. 19, 1150–1158.
Chojnacky, D.C., Heath, L.S., Jenkins, J.C., 2013. Updated generalized biomass equations for North American tree species. Forestry 87, 129–151.
Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogee, J., Allard, V., et al., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437, 529–533.
Ciais, P., Schelhaas, M.J., Zaehle, S., Piao, S.L., Cescatti, A., Liski, J., et al., 2008. Carbon accumulation in European forests. Nat. Geosci. 1, 425–429.
Clark, J.S., Iverson, L., Woodall, C.W., Allen, C.D., Bell, D.M., Bragg, D.C., et al., 2016. The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States. Glob. Chang. Biol. 22, 2329–2352.
Crowther, T.W., Glick, H.B., Covey, K.R., Bettigole, C., Maynard, D.S., Thomas, S.M., et al., 2015. Mapping tree density at a global scale. Nature 525, 201–205.
Dai, A., 2011. Drought under global warming: a review. Wiley Interdiscip. Rev. Clim. Chang. 2, 45–65.
Dai, A., 2012. Increasing drought under global warming in observations and models. Nat. Clim. Chang. 3, 52–58.
Davis, M.B., Shaw, R.G., 2001. Range shifts and adaptive responses to quaternary climate change. Science 292, 673–679.
DeWalle, D.R., Buda, A.R., Fisher, A., 2003. Extreme weather and forest management in the mid-Atlantic region of the United States. North. J. Appl. For. 20, 61–70.
Dhar, A., Parrott, L., Heckbert, S., 2016. Consequences of mountain pine beetle outbreak on forest ecosystem services in western Canada. Can. J. For. Res. 46, 987–999.
Diffenbaugh, N.S., Field, C.B., 2013. Changes in ecologically critical terrestrial climate conditions. Science 341, 486–492.
Donoghue, M.J., Edwards, E.J., 2014. Biome shifts and niche evolution in plants. Annu. Rev. Ecol. Evol. Syst. 45, 547–572.
D'Orangeville, L., Duchesne, L., Houle, D., Kneeshaw, D., Côté, B., Pederson, N., 2016. Northeastern North America as a potential refugium for boreal forests in a warming climate. Science 352, 1452–1455.
Drobyshev, I., Gewehr, S., Berninger, F., Bergeron, Y., 2013. Species specific growth responses of black spruce and trembling aspen may enhance resilience of boreal forest to climate change. J. Ecol. 101, 231–242.
Fei, S., Desprez, J.M., Potter, K.M., Jo, I., Knott, J.A., Oswalt, C.M., 2017. Divergence of species responses to climate change. Sci. Adv. 3, e1603055.
Fettig, C.J., Reid, M.L., Bentz, B.J., Sevanto, S., Spittlehouse, D.L., Wang, T., 2013. Changing climates, changing forests: a western north American perspective. J. For. 111, 214–228.
Flannigan, M.D., Logan, K.A., Amiro, B.D., Skinner, W.R., Stocks, B.J., 2005. Future area burned in Canada. Clim. Chang. 72, 1–16.
Flannigan, M., Stocks, B., Turetsky, M., Wotton, M., 2009. Impacts of climate change on fire activity and fire management in the circumboreal forest. Glob. Chang. Biol. 15, 549–560.
Gauthier, S., Bernier, P., Burton, P.J., Edwards, J., Isaac, K., Isabel, N., et al., 2014. Climate change vulnerability and adaptation in the managed Canadian boreal forest. Environ. Rev. 22, 256–285.
Gauthier, S., Bernier, P., Kuuluvainen, T., Shvidenko, A.Z., Schepaschenko, D.G., 2015a. Boreal forest health and global change. Science 349, 819–822.
Gauthier, S., Bernier, P.Y., Boulanger, Y., Guo, J., Guindon, L., Beaudoin, A., et al., 2015b. Vulnerability of timber supply to projected changes in fire regime in Canada's managed forests. Can. J. For. Res. 45, 1439–1447.

Ge, Z.M., Zhou, X.A., Kellomaki, S., Wang, K.Y., Peltola, H., Vaisanen, H., et al., 2010. Effects of changing climate on water and nitrogen availability with implications on the productivity of Norway spruce stands in Southern Finland. Ecol. Model. 221, 1731–1743.
Ge, Z.M., Kellomaki, S., Peltola, H., Zhou, X., Wang, K.Y., Vaisanen, H., 2011. Impacts of changing climate on the productivity of Norway spruce dominant stands with a mixture of scots pine and birch in relation to water availability in southern and northern Finland. Tree Physiol. 31, 323–338.
Gillett, N.P., Weaver, A., Zwiers, F., Flannigan, M.D., 2004. Detecting the effect of climate change on Canadian forest fires. Geophys. Res. Lett. 31.
Girard, F., De Grandpre, L., Ruel, J.C., 2014. Partial windthrow as a driving process of forest dynamics in old-growth boreal forests. Can. J. For. Res. 44, 1165–1176.
Girardin, M.P., Ali, A.A., Carcaillet, C., Mudelsee, M., Drobyshev, I., Hely, C., et al., 2009. Heterogeneous response of circumboreal wildfire risk to climate change since the early 1900s. Glob. Chang. Biol. 15, 2751–2769.
Girardin, M.P., Guo, X.J., Bernier, P.Y., Raulier, F., Gauthier, S., 2012. Changes in growth of pristine boreal north American forests from 1950 to 2005 driven by landscape demographics and species traits. Biogeosciences 9, 2523–2536.
Girardin, M.P., Ali, A.A., Carcaillet, C., Gauthier, S., Hély, C., Le Goff, H., et al., 2013. Fire in managed forests of eastern Canada: risks and options. For. Ecol. Manag. 294, 238–249.
Girardin, M.P., Bouriaud, O., Hogg, E.H., Kurz, W., Zimmermann, N.E., Metsaranta, J.M., et al., 2016a. No growth stimulation of Canada's boreal forest under half-century of combined warming and CO2 fertilization. Proc. Natl. Acad. Sci. U. S. A. 113, E8406–E8414.
Girardin, M.P., Hogg, E.H., Bernier, P.Y., Kurz, W.A., Guo, X.J., Cyr, G., 2016b. Negative impacts of high temperatures on growth of black spruce forests intensify with the anticipated climate warming. Glob. Chang. Biol. 22, 627–643.
Gonzalez, P., Neilson, R.P., Lenihan, J.M., Drapek, R.J., 2010. Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change. Glob. Ecol. Biogeogr. 19, 755–768.
Greenwood, S., Ruiz-Benito, P., Martinez-Vilalta, J., Lloret, F., Kitzberger, T., Allen, C.D., et al., 2017. Tree mortality across biomes is promoted by drought intensity, lower wood density and higher specific leaf area. Ecol. Lett. 20, 539–553.
Groisman, P.Y., Sherstyukov, B.G., Razuvaev, V.N., Knight, R.W., Enloe, J.G., Stroumentova, N.S., et al., 2007. Potential forest fire danger over Northern Eurasia: changes during the 20th century. Glob. Planet. Chang. 56, 371–386.
Guo, C., Costello, C., 2013. The value of adaption: climate change and timberland management. J. Environ. Econ. Manag. 65, 452–468.
Hanewinkel, M., Cullmann, D.A., Schelhaas, M.J., Nabuurs, G.J., Zimmermann, N.E., 2013. Climate change may cause severe loss in the economic value of European forest land. Nat. Clim. Chang. 3, 203–207.
Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., et al., 2013. High- resolution global maps of 21st-century Forest cover change. Science 342, 850–853.
Hember, R.A., Kurz, W.A., Coops, N.C., 2017. Relationships between individual-tree mortality and water-balance variables indicate positive trends in water stress-induced tree mortality across North America. Glob Chang Biol. 23, 1691–1710.
Hisano, M., Searle, E.B., Chen, H.Y.H., 2018. Biodiversity as a solution to mitigate climate change impacts on the functioning of forest ecosystems. Biol. Rev. Camb. Philos. Soc. 93, 439–456.
Hofgaard, A., Tommervik, H., Rees, G., Hanssen, F., 2013. Latitudinal forest advance in northernmost Norway since the early 20th century. J. Biogeogr. 40, 938–949.
Hope, E.S., McKenney, D.W., Pedlar, J.H., Stocks, B.J., Gauthier, S., 2016. Wildfire suppression costs for Canada under a changing climate. PLoS One 11, e0157425.
Houle, D., Lajoie, G., Duchesne, L., 2016. Major losses of nutrients following a severe drought in a boreal forest. Nat. Plants 2, 16187.
Huang, J.G., Bergeron, Y., Berninger, F., Zhai, L., Tardif, J.C., Denneler, B., 2013. Impact of future climate on radial growth of four major boreal tree species in the Eastern Canadian boreal forest. PLoS One 8, e56758.
Hume, A.M., Chen, H.Y.H., Taylor, A.R., Kardol, P., 2018. Intensive forest harvesting increases susceptibility of northern forest soils to carbon, nitrogen and phosphorus loss. J. Appl. Ecol. 55, 246–255.
Ilisson, T., Chen, H.Y.H., 2009. The direct regeneration hypothesis in northern forests. J. Veg. Sci. 20, 735–744.
IPCC, 2014. Summary for policy makers. In: Pachauri, R.K., Meyer, L.A. (Eds.), Climate Change 2014: Synthesis Report. Contibution of Working Groups I, II, and III to the Fifth Assessment Report if the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.
Jactel, H., Petit, J., Desprez-Loustau, M.-L., Delzon, S., Piou, D., Battisti, A., et al., 2012. Drought effects on damage by forest insects and pathogens: a meta-analysis. Glob. Chang. Biol. 18, 267–276.
Johnson, E.A., 1992. Fire and Vegetation Dynamics: Studies from North American Boreal Forest. Camebridge University Press, Cambirdge.
Johnstone, J.F., Hollingsworth, T.N., Chapin, F.S., Mack, M.C., 2010. Changes in fire regime break the legacy lock on successional trajectories in Alaskan boreal forest. Glob. Chang. Biol. 16, 1281–1295.
Kauppi, P.E., Posch, M., Pirinen, P., 2014. Large impacts of climate warming on growth of boreal forests since 1960. PLoS One 9.
Kellomaki, S., 2000. Forests of the boreal region: gaps in knowledge and research needs. For. Ecol. Manag. 132, 63–71.
Kellomäki, S., Peltola, H., Nuutinen, T., Korhonen, K.T., Strandman, H., 2008. Sensitivity of managed boreal forests in Finland to climate change, with implications for adaptive management. Philos. Trans. R. Soc. B Biol. Sci. 363, 2339–2349.
Keskitalo, E., Bergh, J., Felton, A., Björkman, C., Berlin, M., Axelsson, P., et al., 2016. Adaptation to climate change in Swedish forestry. Forests 7, 28.
Kirilenko, A.P., Sedjo, R.A., 2007. Climate change impacts on forestry. Proc. Natl. Acad. Sci. U. S. A. 104, 19697–19702.
Knoke, T., Ammer, C., Stimm, B., Mosandl, R., 2007. Admixing broadleaved to coniferous tree species: a review on yield, ecological stability and economics. Eur. J. For. Res. 127, 89–101.
Kurz, W.A., Dymond, C.C., Stinson, G., Rampley, G.J., Neilson, E.T., Carroll, A.L., et al., 2008. Mountain pine beetle and forest carbon feedback to climate change. Nature 452, 987–990.
Kurz, W.A., Shaw, C.H., Boisvenue, C., Stinson, G., Metsaranta, J., Leckie, D., et al., 2013. Carbon in Canada's boreal forest — A synthesis1. Environ. Rev. 21, 260–292.
Leduc, A., Bernier, P.Y., Mansuy, N., Raulier, F., Gauthier, S., Bergeron, Y., 2015. Using salvage logging and tolerance to risk to reduce the impact of forest fires on timber supply calculations. Can. J. For. Res. 45, 480–486.
Lempriere, T.C., Bernier, P., Carroll, A.L., Flannigan, M.D., Gilsenan, R.P., McKenney, D.W., et al., 2008. The Importance of Forest Sector Adaptation to Climate Change. Northern Forestry Centre, Canadian Forest Service, Natural Resources Canada.
Liang, J., Crowther, T.W., Picard, N., Wiser, S., Zhou, M., Alberti, G., et al., 2016. Positive biodiversity-productivity relationship predominant in global forests. Science 354.
van Lierop, P., Lindquist, E., Sathyapala, S., Franceschini, G., 2015. Global forest area disturbance from fire, insect pests, diseases and severe weather events. For. Ecol. Manag. 352, 78–88.
Linderholm, H.W., 2006. Growing season changes in the last century. Agric. For. Meteorol. 137, 1–14.
Lindner, M., Sohngen, B., Joyce, L.A., Price, D.T., Bernier, P.Y., Karjalainen, T., 2002. Integrated forestry assessments for climate change impacts. For. Ecol. Manag. 162, 117–136.
Lloyd, A.H., Bunn, A.G., Berner, L., 2011. A latitudinal gradient in tree growth response to climate warming in the Siberian taiga. Glob. Chang. Biol. 17, 1935–1945.
Logan, J., Régnière, J., Powell, J., 2003. Assessing the impacts of global warming on forest pest dynamics. Front. Ecol. Environ. 1, 130–137.
Luo, Y., Chen, H.Y.H., 2011. Competition, species interaction and ageing control tree mortality in boreal forests. J. Ecol. 99, 1470–1480.
Luo, Y., Chen, H.Y.H., 2013. Observations from old forests underestimate climate change effects on tree mortality. Nat. Commun. 4, 1965.
Luo, Y., Chen, H.Y., 2015. Climate change-associated tree mortality increases without decreasing water availability. Ecol. Lett. 18, 1207–1215.
Lutz, D.A., Shugart, H.H., White, M.A., 2013. Sensitivity of Russian forest timber harvest and carbon storage to temperature increase. Forestry 86, 283–293.
Luyssaert, S., Inglima, I., Jung, M., Richardson, A.D., Reichstein, M., Papale, D., et al., 2007. CO_2 balance of boreal, temperate, and tropical forests derived from a global database. Glob. Chang. Biol. 13, 2509–2537.
Malmstrom, C.M., Raffa, K.F., 2000. Biotic disturbance agents in the boreal forest: considerations for vegetation change models. Glob. Chang. Biol. 6, 35–48.
van Mantgem, P.J., Stephenson, N.L., Byrne, J.C., Daniels, L.D., Franklin, J.F., Fulé, P.Z., et al., 2009. Widespread increase of tree mortality rates in the western United States. Science 323, 521–524.
McKenney, D., Yemshanov, D., Pedlar, J., Allen, D., Lawrence, K., Hope, E., et al., 2016. Canada's Timber Supply: Current Status and Future Prospects under a Changing Climate.
Mendelsohn, R., Morrison, W., Schlesinger, M., Andronova, N., 2000. Country-specific market impacts of climate change. Climate Change 45, 553–569.
Michaelian, M., Hogg, E.H., Hall, R.J., Arsenault, E., 2011. Massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest. Glob. Chang. Biol. 17, 2084–2094.
Millar, C.I., Stephenson, N.L., 2015. Temperate forest health in an era of emerging megadisturbance. Science 349, 823–826.
Montwe, D., Isaac-Renton, M., Hamann, A., Spiecker, H., 2016. Drought tolerance and growth in populations of a wide-ranging tree species indicate climate change risks for the boreal north. Glob. Chang. Biol. 22, 806–815.
Moritz, M.A., Parisien, M.-A., Batllori, E., Krawchuk, M.A., Van Dorn, J., Ganz, D.J., et al., 2012. Climate change and disruptions to global fire activity. Ecosphere 3, 1–22.
Nabuurs, G.J., Pussinen, A., Karjalainen, T., Erhard, M., Kramer, K., 2002. Stemwood volume increment changes in European forests due to climate change - a simulation study with the EFISCEN model. Glob. Chang. Biol. 8, 304–316.
NRTEE, 2011. Paying the price: The economic impacts of climate change for Canada. National round table on the economy and environment, a canadian initiative.
Ochuodho, T.O., Lantz, V.A., Lloyd-Smith, P., Benitez, P., 2012. Regional economic impacts of climate change and adaptation in Canadian forests: a CGE modeling analysis. Forest Policy Econ. 25, 100–112.
Ozolincius, R., 2012. Possible effects of climate change on Forest biodiversity, tree growth and condition: review of research in Lithuania. Balt. For. 18, 156–167.
Park, A., Puettmann, K., Wilson, E., Messier, C., Kames, S., Dhar, A., 2014. Can boreal and temperate Forest management be adapted to the uncertainties of 21st century climate change? Crit. Rev. Plant Sci. 33, 251–285.
Parmesan, C., Yohe, G., 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature 421, 37–42.
Pautasso, M., Schlegel, M., Holdenrieder, O., 2015. Forest health in a changing world. Microb. Ecol. 69, 826–842.
Pearson, R.G., 2006. Climate change and the migration capacity of species. Trends Ecol. Evol. 21, 111–113.
Pecl, G.T., Araújo, M.B., Bell, J.D., Blanchard, J., Bonebrake, T.C., Chen, I.C., et al., 2017. Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. Science 355.
Pedlar, J.H., McKenney, D.W., 2017. Assessing the anticipated growth response of northern conifer populations to a warming climate. Sci. Rep. 7, 43881.
Peltola, H., Ikonen, V.P., Gregow, H., Strandman, H., Kilpeläinen, A., Venäläinen, A.,

et al., 2010. Impacts of climate change on timber production and regional risks of wind-induced damage to forests in Finland. For. Ecol. Manag. 260, 833–845.
Peng, C., Ma, Z., Lei, X., Zhu, Q., Chen, H., Wang, W., et al., 2011. A drought-induced pervasive increase in tree mortality across Canada's boreal forests. Nat. Clim. Chang. 1, 467–471.
Peñuelas, J., Canadell, J.G., Ogaya, R., 2011. Increased water-use efficiency during the 20th century did not translate into enhanced tree growth. Glob. Ecol. Biogeogr. 20, 597–608.
Perez-Garcia, J., Joyce, L.A., McGuire, A.D., Xiao, X.M., 2002. Impacts of climate change on the global forest sector. Clim. Chang. 54, 439–461.
Perie, C., de Blois, S., 2016. Dominant forest tree species are potentially vulnerable to climate change over large portions of their range even at high latitudes. Peer J. 4, e2218.
Pretzsch, H., Biber, P., Schutze, G., Uhl, E., Rotzer, T., 2014. Forest stand growth dynamics in Central Europe have accelerated since 1870. Nat. Commun. 5, 4967.
Price, D.T., Alfaro, R.I., Brown, K.J., Flannigan, M.D., Fleming, R.A., Hogg, E.H., et al., 2013. Anticipating the consequences of climate change for Canada's boreal forest ecosystems1. Environ. Rev. 21, 322–365.
Pukkala, T., 2017. Transfer and response functions as a means to predict the effect of climate change on timber supply. Forestry: An International Journal of Forest Research 1–8.
Pureswaran, D.S., De Grandpre, L., Pare, D., Taylor, A., Barrette, M., Morin, H., et al., 2015. Climate-induced changes in host tree-insect phenology may drive ecological state-shift in boreal forests. Ecology 96, 1480–1491.
Ramsfield, T.D., Bentz, B.J., Faccoli, M., Jactel, H., Brockerhoff, E.G., 2016. Forest health in a changing world: effects of globalization and climate change on forest insect and pathogen impacts. Forestry 89, 245–252.
Reyer, C.P.O., Brouwers, N., Rammig, A., Brook, B.W., Epila, J., Grant, R.F., et al., 2015. Forest resilience and tipping points at different spatio-temporal scales: approaches and challenges. J. Ecol. 103, 5–15.
Reyer, C.P.O., Bathgate, S., Blennow, K., Borges, J.G., Bugmann, H., Delzon, S., et al., 2017. Are forest disturbances amplifying or canceling out climate change-induced productivity changes in European forests? Environ. Res. Lett. 12, 034027.
Rittenhouse, C.D., Rissman, A.R., 2015. Changes in winter conditions impact forest management in north temperate forests. J. Environ. Manag. 149, 157–167.
Rogers, B.M., Soja, A.J., Goulden, M.L., Randerson, J.T., 2015. Influence of tree species on continental differences in boreal fires and climate feedbacks. Nat. Geosci. 8, 228–234.
Rowland, L., da Costa, A.C., Galbraith, D.R., Oliveira, R.S., Binks, O.J., Oliveira, A.A., et al., 2015. Death from drought in tropical forests is triggered by hydraulics not carbon starvation. Nature 528, 119–122.
Ruthrof, K.X., Fontaine, J.B., Matusick, G., Breshears, D.D., Law, D.J., Powell, S., et al., 2016. How drought-induced forest die-off alters microclimate and increases fuel loadings and fire potentials. Int. J. Wildland Fire 25, 819.
Sato, H., Kobayashi, H., Iwahana, G., Ohta, T., 2016. Endurance of larch forest ecosystems in eastern Siberia under warming trends. Ecol. Evol. 6, 5690–5704.
Savage, D.W., Martell, D.L., Wotton, B.M., 2010. Evaluation of two risk mitigation strategies for dealing with fire-related uncertainty in timber supply modelling. Can. J. For. Res. 40, 1136–1154.
Schaphoff, S., Reyer, C.P.O., Schepaschenko, D., Gerten, D., Shvidenko, A., 2016. Tamm review: observed and projected climate change impacts on Russia's forests and its carbon balance. For. Ecol. Manag. 361, 432–444.
Schlyter, P., Stjernquist, I., Barring, L., Jonsson, A.M., Nilsson, C., 2006. Assessment of the impacts of climate change and weather extremes on boreal forests in Northern Europe, focusing on Norway spruce. Clim. Res. 31, 75–84.
Searle, E.B., Chen, H.Y., 2017. Persistent and pervasive compositional shifts of western boreal forest plots in Canada. Glob. Chang. Biol. 23, 857–866.
Seidl, R., Rammer, W., Jäger, D., Lexer, M.J., 2008. Impact of bark beetle (Ips typographus L.) disturbance on timber production and carbon sequestration in different management strategies under climate change. For. Ecol. Manag. 256, 209–220.
Shuman, J.K., Tchebakova, N.M., Parfenova, E.I., Soja, A.J., Shugart, H.H., Ershov, D., et al., 2015. Forest forecasting with vegetation models across Russia1. Can. J. For. Res. 45, 175–184.
Shvidenko, A.Z., Schepaschenko, D.G., 2014. Climate change and wildfires in Russia. Contemp. Probl. Ecol. 6, 683–692.
Sitch, S., Huntingford, C., Gedney, N., Levy, P.E., Lomas, M., Piao, S.L., et al., 2008. Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs). Glob. Chang. Biol. 14, 2015–2039.
Sohngen, B., 2014. Forests and climate change: economic perspectives. In: Kant, S., Alavalapati, J.R.R. (Eds.), Handbook of Forest Reouce Economics. Routledge, London, UK and New York, USA, pp. 227–242.
Sohngen, B., Tian, X., 2016. Global climate change impacts on forests and markets. Forest Policy Econ. 72, 18–26.
Sohngen, B., Mendelsohn, R., Sedjo, R., 2001. A global model of climate change impacts on timber markets. J. Agr. Resour. Econ. 26, 326–343.
Soja, A.J., Tchebakova, N.M., French, N.H.F., Flannigan, M.D., Shugart, H.H., Stocks, B.J., et al., 2007. Climate-induced boreal forest change: predictions versus current observations. Glob. Planet. Chang. 56, 274–296.
Solberg, B., Moiseyev, A., Kallio, A.M.I., 2003. Economic impacts of accelerating forest growth in Europe. Forest Policy Econ. 5, 157–171.
Sturrock, R.N., 2012. Climate change and forest diseases: using today's knowledge to address future challenges. Forest Systems 21, 329–336.
Tchebakova, N.M., Parfenova, E.I., Soja, A.J., 2011. Climate change and climate-induced hot spots in forest shifts in Central Siberia from observed data. Reg. Environ. Chang. 11, 817–827.
Tchebakova, N.M., Parfenova, E.I., Korets, M.A., Conard, S.G., 2016. Potential change in forest types and stand heights in Central Siberia in a warming climate. Environ. Res. Lett. 11.
Terrier, A., Girardin, M.P., Perie, C., Legendre, P., Bergeron, Y., 2013. Potential changes in forest composition could reduce impacts of climate change on boreal wildfires. Ecol. Appl. 23, 21–35.
Thomson, A.M., Parker, W.H., 2008. Boreal forest provenance tests used to predict optimal growth and response to climate change. 1. Jack pine. Can. J. For. Res. 38, 157–170.
Thuiller, W., 2007. Biodiversity: climate change and the ecologist. Nature 448, 550–552.
Tian, X., Sohngen, B., Kim, J.B., Ohrel, S., Cole, J., 2016. Global climate change impacts on forests and markets. Environ. Res. Lett. 11, 035011.
Toledo, M., Poorter, L., Peña-Claros, M., Alarcón, A., Balcázar, J., Leaño, C., et al., 2011. Climate is a stronger driver of tree and forest growth rates than soil and disturbance. J. Ecol. 99, 254–264.
Trenberth, K.E., Dai, A., van der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R., et al., 2013. Global warming and changes in drought. Nat. Clim. Chang. 4, 17–22.
Weed, A.S., Ayres, M.P., Hicke, J.A., 2013. Consequences of climate change for biotic disturbances in North American forests. Ecol. Monogr. 83, 441–470.
Zhang, S.Y., 1994. Effect of growth rate on wood specific gravity and selected mechanical properties in individual species from distinct wood categories. Wood Sci. Technol. 29, 451–465.
Zhang, D., Pearse, P., 2011. Forest Economics. UBC Press, Vancouver, British Columbia.
Zhang, Y., Chen, H.Y.H., Reich, P.B., 2012. Forest productivity increases with evenness, species richness and trait variation: a global meta-analysis. J. Ecol. 100, 742–749.
Zhao, M.S., Running, S.W., 2010. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. Science 329, 940–943.
Zhu, J.Y., Scott, C.T., Scallon, K.L., Myers, G.C., 2007. Effects of plantation density on wood density and anatomical properties of red pine (Pinus resinosa Ait.). Wood Fiber Sci. 39, 502–512.